# Autonomous, Biologically Inspired Systems for Future Aerospace Missions

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The early twenty-first century will witness a new era of space exploration characterized by sustained in-depth scientific studies at increasingly remote environments with themes as compelling as the search for life in the universe. The goals of these activities include vigilant intelligent presence in the solar system; exploration of interstellar space; discovery of earth-like planets around nearby stars with a telescope powerful enough to determine signs of life 600 trillion miles away. An integrated human-robotic exploration strategy, well beyond the space station, is being developed for the solar system and beyond that focuses on enhancing the safety, improving the performance, expanding the mission objectives, and minimizing the life cycle costs.

The realization of these ambitious goals with the current budget constraints requires new kinds of missions and space systems that utilize novel technologies and manage risks in new ways. Future systems need to combine a number of major characteristics, including autonomy, evolvability, resilience, and be highly distributed. In addition, the systems must be able to: a) perform their missions with no, or extremely infrequent, ground support; b) exploit and utilize local resources; and c) routinely close decision loops in real-time for contingency handling and mission re-planning when necessary. These characteristics require integrated technologies and are highly coupled. The present article focuses on autonomy, evolvability and highly distributed characteristics. The first is a practical application of AI and the last two are biologically inspired.

**Autonomy**

Autonomy refers to the ability of the space system to learn and adapt its performance to environmental conditions and against degradation. In deep space missions, the uncertainty about hazardous terrain, the great distances from earth and the attendant communication delays will require that the system (probe or rover) be able to autonomously navigate, select and track targets, maneuver over a wide variety of surfaces, and independently perform several kinds of tasks. The tasks include surveys and evaluations of potential sites, recognizing science opportunities, performing data evaluation and observation planning, and gathering samples.

In combined human-robotic exploration missions, the driving consideration is to find the right way to combine human and machine intelligence into a single, effective system. An autonomous system can perform several useful support functions for scientists, astronauts and ground operations personnel, such as automated planning, scheduling and resource management, condition-based maintenance and diagnosis, and some forms of intermediate science data analysis.

**Components of Space System Autonomy**

The software capabilities that contribute to space system autonomy can be grouped into six categories:

- *Automated guidance, navigation and control*, which includes target-body characterization and orbit determination, precise pointing of instruments, landmark recognition and hazard detection during landing, and formation flying.

- *Mission planning, scheduling and resource management.* Activities in this category are related to high-level mission goals, re-planning when science or engineering events occur, and continuous management of on-board resources.
- *Model-based fault management*, which comprises anomaly detection, fault diagnosis and fault recovery. This capability enables designers to achieve reliable fault protection without comprehensive space-platform safing, with loss of mission context.
- *Onboard science data processing*, including trainable object recognizers and knowledge discovery methods applied to prioritizing science data for down-link, and for identifying possible science opportunities for further evaluation by principal investigators (PIs).
- *Autonomy architecture and software engineering*, which are the glue that binds together all the aforementioned capabilities. The activities in this area include design of modeling tools and modeling languages, code and test generation, and development of autonomy software testing concepts.

**Strategic Value of Autonomy**

Space system autonomy will pay off in three inter-related ways:

- Reducing mission life-cycle cost
- Improving mission operations, and
- Enabling bolder and unprecedented mission concepts.

The first is achieved through migrating several of the traditionally ground-based functions to the space system, thereby enabling a paradigm shift from large ground teams for each mission to smaller ground teams shared among several missions.

The second strategic value is achieved through near real-time analysis of science data onboard the spacecraft. This onboard analysis offers two advantages: making more efficient and flexible use of the limited communication links between the ground and space platform - through down-link prioritization and, in some cases, the onboard construction of more compact and useful science information from the raw data; and capturing transient opportunities that require the quick, reliable recognition of scientifically important events. The goal is to provide a direct link between PIs at their home institutions and the onboard software directing mission activities.

The third strategic value is achieved when new space exploration is accomplished via mission concepts that naturally entail autonomy. We are already seeing the first of these new mission classes: the *in-situ* missions, characterized by space platforms experiencing ongoing interactions with a planetary environment; and the *constellation* missions, where several space platforms must coordinate to accomplish mission objectives. Examples of these new, bold missions are described subsequently in the sidebar entitled, "Mission Concepts Being Developed at NASA."

Despite its strategic value, autonomy implies a trade between predictability and robustness in execution. Assessments are currently being made of technological maturity, risk, feasibility from a systems-engineering viewpoint, and actual benefits.

**Evolvability**

Evolvability of a space system can be manifested in a variety of ways including: a) dynamic changes of architecture, structure and functions of the system to improve performance of certain tasks; b) adaptive reconfiguration for long life and purposeful survival (e.g., against degradation); and c) creating new functionality for changes in requirements, and/or environment. The dynamic changes and adaptive reconfiguration of the system include both the software and hardware.

Evolvability is expected to have a major impact on deployable systems for space missions that need to perform at optimal functionality during long periods in unknown harsh and/or changing environments. Examples include outer solar system exploration, missions to comets and planets that have severe environmental conditions, applications needing adaptive information processing (such as human-oriented hardware interfaces and Internet adaptive hardware).

Revolutionary advances in component system robustness (e.g., via onboard reasoning capability and adaptable materials and structures), along with evolvability concepts, can lead to a space platform lifetime of unprecedented length (e.g., a few decades to a century).

To achieve mission continuation despite unexpected and potentially compromising external events and failure, the system must be fault tolerant with self-repair capability, i.e. it has onboard fully automated self-assessment and self-reconfiguration as defense against faults. Also, onboard acumen can be used as an extension to hardware redundancy and other forms of fault tolerance. Inspiration also can be gained from the contribution of immune systems to the survivability of biological systems.

**Highly Distributed Systems – Robotic Outposts**

To achieve maximum capability for space exploration and communication, the concept of "robotic outposts" is being considered. A robotic outpost is a remote highly distributed scientific research station similar to an insect or a human society, but operating autonomously using multiple cooperating robotic platforms. The highest level of autonomy would correspond to the use of intelligent robots that are given only the top-level goals. They would, in turn, determine their own immediate objectives in pursuit of those goals using only occasional consultation with remote human directors.

The concept of robotic outposts is an outgrowth of the extensive work done on multi-agent systems and cooperative robots, a branch of distributed artificial intelligence, covering distributed diagnosis, resource management and execution, and coordination of heterogeneous reasoning methods. In the development of robotic outposts, a key challenge is to create systems that exhibit the desirable characteristics of fault tolerance, reliability and adaptivity. A fault tolerant system should be able to detect and gracefully compensate for partial system failures, thus minimizing its vulnerability to individual robot outages. A reliable cooperative system should guarantee that its mission would be accomplished, within certain operating constraints, each time it is utilized, and, an adaptable robot team should be able to dynamically modify its actions as the environment or individual robot characteristics change over time.

Robotic outposts can be used to extend human senses into the solar system, and could serve as precursors to human presence. They would be permanent and selfsustaining with occasional re-supply. They could be deployed as expandable intelligent stations in space, on near-earth objects, such as asteroids and comets, on the moon, Mars or elsewhere. They could conduct planetary in-situ studies or remote astrophysical observations, and they could set the stage for later human participation if and when it was decided to send human explorers.

**Future Missions**

Future space missions will go beyond reconnaissance and involve sustained in-situ scientific studies. Such missions were not previously within reach because they require the space platform to operate in a closed-loop fashion in its environment. In constellation missions comprising multiple space platforms, loop closing takes the form of coordination among platforms carrying different assets. An example of this is space-born detection of earth-grazing asteroids and comets. The first platform to detect such an event might not have the appropriate instrument for studying it, but when it sends out an alert across the entire fleet, other instruments can be brought to bear, each platform making its own decision on whether and how to contribute to the study of the event.

A wealth of technological breakthroughs are likely to come from mimicking the interactions of biological systems and their response to the environment. The new millenium will witness thinking, learning, evolvable spacecraft, as well as systems on a chip - miniaturization of all electronic systems of a spacecraft (computer and memory, guidance, navigation, communications, power and sensors, all into a tiny chip). The payoff for such technological brashness will be the ability to reinvent what forms of exploration at the absolute frontier have come within reach.

## Biological Inspiration for Future Space Systems

Over the past few years, a growing number of engineers have been seeking inspiration from biological systems to augment the capabilities of their artificially engineered systems. The overall goal of bio-inspired systems is the creation of more adaptive systems – systems that are able to undergo modifications according to changing environmental conditions or circumstances, thereby ensuring their continued functionality. The systems evolve, develop and learn (i.e., they adapt on their own, with no human intervention). Research in this area can be traced back to the cybernetics movement of the 1940's and 50's. It has recently resurged in the form of the nascent field of *evolvable hardware* (EHW) and *bio-mimetic systems*. EHW allows the dynamic adaptation of the hardware structure to the problem. The field draws on ideas from the evolutionary computation domain as well as on hardware innovations. Adaptive configurable electronic hardware, such as field programmable gate arrays (FPGAs), is an example of EHW. These are capable of online adaptation by reconfiguring their architecture dynamically and autonomously. This can be accomplished by downloading into the device a software bit string called configuration bits. The firefly machine and the bio-watch are two examples of bio-inspired hardware, built at the Logic Systems Laboratory in Switzerland. The firefly is based on the cellular automata model and exhibits complete online evolution. All its operations are carried out in hardware with no reference to an external computer. The bio-watch is designed to demonstrate the two bio-inspired properties of self-repair and self-replication. Self-repair allows partial reconstruction of the original device in case of a minor fault. Self-replication assumes the existence of spare cells in the hardware and design or blueprint information in the software.

Another biologically inspired area being explored is *emotional computation*. There is psychological and neurological evidence that emotion may play an important role in decision making in humans. Electroencephalogram (EEG – electrical activity produced by neurons in the brain and recorded from the scalp) studies show a great deal of communication between the limbic system and the cortex during decision making. Moreover, brain injured humans who have had these connections severed have shown an inability to make decisions.

For future space systems, emotional computation may play a role if such a capability can give rise to useful behaviors, particularly for decision making. For example, the computational state corresponding to unacceptable uncertainty in modeling context or environment may be interpreted as fear, and is useful if it triggers responses such as locomotion, or additional information gathering. Similarly, when a high-level background goal is serendipitously achieved in the course of mission activities (surprise), a useful behavior may be to allocate additional resources to attend to the event. To give one more example, sustained low variance of events and problem-solving activities (boredom), may usefully trigger an agent to dynamically reprioritize tasks.

At first glance, emotion, in machines or in space systems, may seem terribly exotic and perhaps ill advised, but when interpreted as computational states and desirable behaviors, emotional computation may indeed be an important ingredient of future autonomous systems, space borne and otherwise.

Other desirable biologically inspired characteristics for future aerospace systems include:

*Tenacity* – determined mission continuation no matter what events might occur.

*Resourcefulness* – solving problems with whatever means are available.

*Curiosity* – deep-seated motivation to explore, investigate and discover.

*Creativity* – ability to bring fresh viewpoints to bear on problems to be solved and goals to pursue.

Among the biologically-inspired aerospace systems being studied at JPL are *bio-morphic explorers*, which are small, dedicated low-cost explorers that capture some of the key features of biological explorers, including:

- Reconfigurable units with versatile mobility (e.g. aerial, surface and sub-surface explorers)

- Control by adaptive fault-tolerant, bio-inspired algorithms to autonomously match changing ambient/terrain conditions.

These features enable comprehensive exploration at lower cost with broader coverage through cooperative organization of lander, rover and a variety of inexpensive low-mass bio-morphic explorers (e.g., bio-morphic gliders, balloon and powered aircraft).

## Mission Concepts Being Developed at NASA

The space exploration mission concepts described herein, as a rule, require the space system characteristics described in this article. Many of these mission concepts would have been considered unreasonable only a few years ago. In the natural course of events, some of these mission concepts will not be approved as NASA mission starts, but there is every expectation that the concepts they embrace will go forward in one way or another.

*Mars* is a primary target for future exploration and certainly has captured the interest of the general public. The Mars missions under development differ from previous space exploration in one important aspect: they are being conceived as a collective whole, with the establishment and evolution of an infrastructure on Mars as an important sub-goal. Such a proposed infrastructure includes permanent science stations on the surface, propellant production plants, and a network of communications satellites in orbit to extend Internet-like capability to Mars, and to enable the coordination of an array of heterogeneous, autonomous explorers: rovers, balloons, airplanes, perhaps even subsurface devices. No longer would each mission be conceived and executed in isolation but through a combination of in-situ and constellation mission concepts. Humanity's presence on Mars would continually expand, culminating in the arrival and safe return of the first human explorers. (Figure 1).

A number of other mission concepts under development for the next wave of solar system exploration require autonomy not only because of the in-situ nature of the missions and in some cases, the extreme planetary environments, but because communication with earth may be difficult or even absent for extended periods. Among these proposed missions is the *Venus Sample Return Mission*, which would place a lander on the surface of Venus, collect samples during the lander's brief lifetime, and efficiently return these samples via a combination of balloon ascent, orbital transfer, and earth return vehicle. Landing, surface and ascent operations are performed autonomously in this mission concept. (Figure 2).

The *Comet Nucleus Sample Return Mission* also involves autonomous landing and return of samples. However, the cometary environment will likely be more unpredictable and potentially volatile, amplifying the requirements for hazard detection and avoidance capabilities during descent and while on the surface. This mission concept calls for multiple site investigations, i.e. there will be multiple landings in the course of the mission. Interestingly, the engineering and science considerations begin to merge in this kind of mission, as the phenomena that represent potential engineering hazards (e.g. jet formation) are also the phenomena of scientific interest. (Figure 3).

*Europa* is a notable focus for future exploration, second only to Mars as a target of interest within the solar system. The reason, of course, is the possibility that a liquid water ocean may exist beneath its surface, with obvious implications for the search for life. Three mission concepts for Europa exploration are at various stages of maturity: the *Europa Orbiter Mission*, approved and set to launch in 2003, which could resolve the question of whether the subsurface ocean exists or not, followed by the *Europa Lander*, and perhaps by a *Europa Cyrobot/Hydrobot Mission*. The Lander would have similar challenges of safe landing and surface operations as described above, plus the additional complication of survivability in the intense radiation environment at Europa, deeply embedded in the Jovian magnetosphere. If the Europa ocean does indeed exist, the

Cryobot/Hydrobot mission concept involves melting through the ice surface of Europa, then releasing an underwater submersible to reach and explore the ocean floor, looking for signs of life. The submersible would require high degrees of autonomy, including onboard algorithms embodying knowledge of biosignatures, in order to perform its mission. (Figure 4).

The *Titan Organics Explorer* would utilize a combination of platform concepts to conduct pre-biological chemistry and atmospheric investigations at Saturn's intriguing satellite, long known to possess an atmosphere, organic materials, and the possibility of a non-water ocean in an entirely different temperature regime. The platform concepts for this mission include an orbiter combined with aerobot/rover deployables. Aerobots utilize natural thermal cycles to periodically go aloft to sample multiple sites over a wide range of territory. When worthy science sites are found, the in-situ investigation capabilities of surface explorers like rovers are utilized. This type of exploration has a random element, however, since landings can be only semi-directed, using direct control of the vertical dimension only along with knowledge of wind patterns. (Figure 5).

Looking beyond the solar system, NASA has a series of next generation deep sky observing missions planned in its Origins Program, whose end goal is the capability to image earth-like planets around nearby stars, even to resolve features and perform spectroscopic investigations of such planets. The hallmark mission in this series is known as the *Terrestrial Planet Finder*, a deep-space-based interferometer consisting of multiple elements. These elements are guided at unprecedented precision (via interference effects) to first null the light coming from the primary star in these distant stellar systems, then collect the precious photons coming from any planetary companions it may possess. The autonomy challenge in this mission is both guidance and control of the interferometer itself during observations, and detection of and compensation for faults and performance degradations in the elements such that the collective capability of the multiple platform interferometer is maintained. (Figure 6).

NASA has also begun the first in-depth studies of *interstellar exploration mission* concepts. The critical path capability for these missions is propulsion, and possibilities include nuclear fusion, matter/anti-matter reactions, and beamed energy light sails. Autonomy, survivability, and evolvability are required for a mission of this type, where the required platform lifetimes would be measured in decades, two-way communication is simply not a possibility, performance degradations and faults are inevitable, and the science mission objectives will be ill-defined at launch time. It is a testament to the bold thinking and the emerging accomplishments of technologists from multiple disciplines that interstellar exploration mission concepts, truly at the frontier of what humanity can imagine, are at this time under serious study. (Figure 7).

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Figure 1.

Mars Exploration.

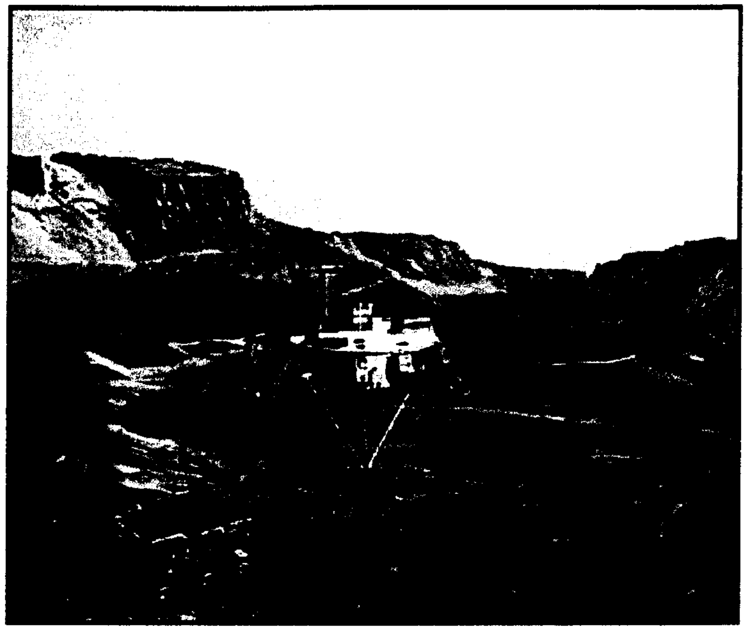

Figure 2.

Venus Sample Return.

Figure 3.

Comet Nucleus Sample Return.

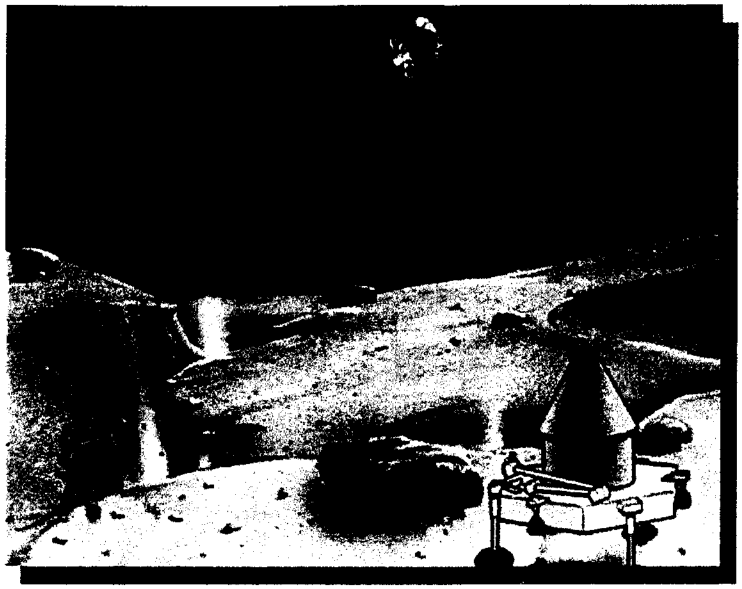

Figure 4.

Europa Exploration.

Figure 5.

Titan Organics Explorer.

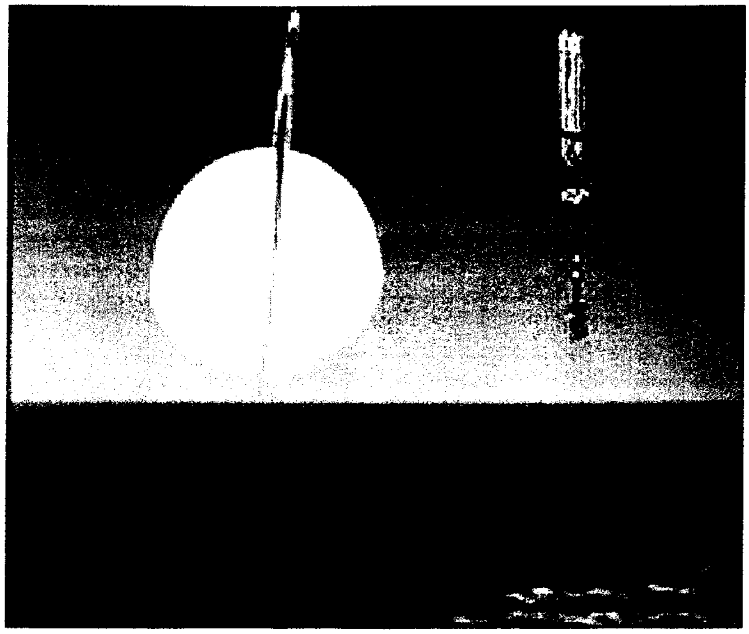

Figure 6.

Terrestrial Planet Finder.

Figure 7.

Interstellar Exploration.